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DESIGN OF ROBUST CONTROLLER FOR AUTOMATIC VOLTAGE REGULATOR (AVR) IN POWER SYSTEM

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ABSTRACT:

Due to ever increasing load demand, electrical power system is operating under highly stressed conditions. Any internal or external disturbance can produce oscillations in the power system. Power system oscillations and their damping is a major challenge for electricity supply industry. Load state changing as dynamic system behaviour will change the current flow in the generator system that result in armature voltage and terminal voltage change. Inductive loads leads to a voltage drop and capacitive load leads to a voltage rise and result in variation of voltage from its rated value. To overcome this problem the generator excitation is controlled by Automatic Voltage Regulator (AVR) which is widely used to deal with the issues of maintaining terminal voltage and improving transient stability of the power system. AVR incorporates an appropriate control system which is having the capability to bring the voltage of the Power system back to original set point effectively after the load change. This can be achieved by using Conventional controllers but these controllers are very slow in operation. The H∞ controller can be used with AVR to get faster and better results. The H∞ control method provides good robust performance under changing load disturbances. In this paper, H∞ controller is designed for AVR. The adjustments in the parameters of the weight functions are achieved by "Automatic Weight Selection Algorithm" The simulations are done using MATLAB software. Reduction in settling time, overshoot and voltage deviation were successfully obtained by using Robust H∞ controller with AVR in Power system.

Keywords: Automatic Voltage Regulator (AVR), Conventional Controllers, Robust H∞ controller, Automatic Weight Selection Algorithm.

1. INTRODUCTION

The Power system is mainly concerned with the generation of electric power from sending to receiving end as per consumer requirements with minimum amount of losses. Power system network is designed to operate at certain nominal frequency and terminal voltages. Any deviation to this may cause dynamic instability within the system which may leads to overall system collapse and may cause damage to connected equipment. Change in reactive power mainly affects the system voltage while change in real power is sensitive to change in system frequency. Therefore real and reactive powers are controlled separately with the use of well control equipment in the generation, substation or distribution substation. The power system researchers round the globe are working meticulously to maintain these two vital parameters at nominal level. Control equipment for the generation is usually used to regulate the supply of active and reactive power. Thus, a control

system cancels the effect of the random load changes and to keep the frequency and voltage, at standard values. The growth in size and complexity of electric power systems along with increase in power demand has initiated the need for intelligent systems that combine different techniques and methodologies **[1].** The automatic control system detects these changes and initiates in real time as set of control actions which will eliminate as effectively and quickly as possible the state deviations. The Automatic Voltage Regulator (AVR) plays an essential role to regulate the voltage magnitude and reactive power whereas active power and system frequency is controlled by Load Frequency Control (LFC). Over the past few decades, several control techniques have been developed. The classical proportional-integral-derivative (PID) controller is the well known among them. Therefore, many methods have been used for fine tuning the PID controller parameters. The setting of the PID controller parameters is cumbersome, especially in industrial systems that have nonlinearities, high order, and delay time. Generally, it is difficult to achieve the best performance of the system by using these methods **[2-6].** A variety of controller design techniques are available in literature, among these, H∞ are one of the most popular techniques for controller designs which ensure robustness, disturbance rejection and perfect stability of the system. The main purpose of the controller is that it can capture bounded uncertainties and reject disturbance **[7].** The control objective of the H∞ controller is to achieve the design parameters by minimizing the norm of the closed loop system **[8].** This Paper explains H∞ controller design procedure for AVR. This technique is mainly applied in linear domain and results in better robustness. Most important task in H∞ controller design method is the selection of weight functions. There are usually two weights in the design process. One is input weight and the other is output weight. These weights are used to normalize the input and output command **[11].** The adjustments in the parameters of the weight functions are achieved by “Automatic Weight Selection Algorithm” **[12].** The advantage of H∞ controller is that the control effort generated by this technique is under limits and can be easily applied to the plant.

II. LITERATURE REVIEW

Hany M. Hasanien proposed the Genetic Algorithm method to optimally design a PID controller in the Automatic Voltage Regulator for improving the step response of terminal voltage. The proportional gain, the integral gain, the derivative gain, and the saturation limit were chosen to define the search space for the optimization problem. As a result of this proposed approach, fast design and an accurate performance prediction were achieved. Therefore, when this proposed approach is applied, it is more efficient in raising the precision of optimization **[1].** Hestikah Eirene Patoding and Eodia T. Lobo proposed the right location for the installation of a PID controller in the AVR system installed after load changes input (before the AVR system) so that the load changes the affect voltage can be set. AVR's performance becomes lighter in controlling the voltage on the existing tolerance. P and PID controllers conducted in disturbance conditions or changes in load indicated that the PID controller is better than the P controller to control the voltage in times of load changes **[2].** Ashok Singh proposed ZN Tuned controller which is more effective means for improving the dynamic performance of the AVR and LFC. The proposed controller still achieves good dynamic performance when the other controller such as PID Controller and without controller response. The simulation results show that the proposed controller can perform an efficient search that achieves better performance criterion through also, the ZN tuned controller response is more superior **[3].**

III. AUTOMATIC VOLTAGE REGULATOR (AVR)

The heart of the excitation systems lies in the voltage regulators. It is a device that serves the output voltage change and provides corrective actions to take place for an isolated generator feeding a load. The Automatic Voltage Regulator (AVR) functions to maintain the bus bar voltage constant.

The AVR has the following objectives, **[13]**

1. To keep the system voltage constant so that the connected equipment operates satisfactorily.

2. To obtain a suitable distribution of reactive load between machines working in parallel.

3. To improve stability of the Power system.

The AVR senses the terminal voltage and adjust the excitation to maintain a constant terminal voltage. It also maintains the reactive power at the required level. The schematic diagram of a simplified AVR is shown in Fig. 1.

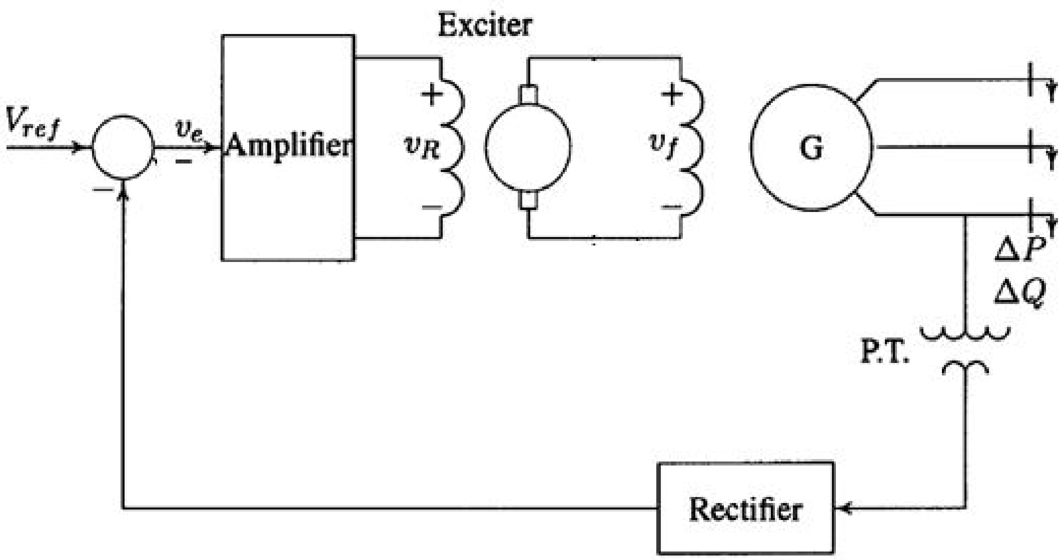

FIGURE 1: GENERAL MODEL OF AVR [18]

IV. MATHEMATICAL MODELING OF AUTOMATIC VOLTAGE REGULATOR

In control system design, initially mathematical modeling of the system is performed. Without mathematical modeling it is almost impossible to design a controller for the system. Controller can be designed by using the practical results of the system but directly performing on practical system, is a risky task. By mathematical modeling, one can conduct proper analysis of the system. Hence, it is important to develop a mathematical model for checking the performance and stability of the Automatic Voltage Regulator **[18]**.

AMPLIFIER MODEL

The excitation amplifier may be rotating amplifier, magnetic amplifier or modern electronic amplifier. The amplifier is represented by gain with K_A symbol and time constant T_A and the transfer function is given as:

$$\frac{\mathbf{V_R(s)}}{\mathbf{V_e(s)}} = \frac{\mathbf{K_A}}{\mathbf{1+T_A}} \quad \textbf{(1)}$$

The value of K_A ranged from 10 to 400, Time constant T_A ranged 0.02 to 0.1 seconds.

EXCITER MODEL

As the output voltage of exciter is nonlinear function so there is no simple relationship between field voltage and terminal voltage. In simplest form the transfer function of exciter ignoring the saturation or other nonlinearities can be represented by single time constant T_E and gain K_E:

$$\frac{\mathbf{V_F(s)}}{\mathbf{V_R(s)}} = \frac{\mathbf{K_E}}{\mathbf{1+T_E}} \quad \textbf{(2)}$$

The value of K_E range 10 to 400, Time constant T_E between 0.5 to 1 seconds.

GENERATOR MODEL

In linearized model the transfer function relating the generator terminal voltage to its field voltage can be represented by gain K_G and time constant T_G and the transfer function is given as:

$$\frac{\mathbf{V_t(s)}}{\mathbf{V_F(s)}} = \frac{\mathbf{K_G}}{\mathbf{1+T_G}} \quad \textbf{(3)}$$

The value of K_G range 0.7 to 1.0, Time constant T_G ranged 1.0 to 2.0 from full load to zero loads.

SENSOR MODEL

Voltage is sensed by potential transformer. It is then rectified through bridge rectifier. Sensor is modelled with a simple first order transfer function,

$$\frac{\mathbf{V_t(s)}}{\mathbf{V_F(s)}} = \frac{\mathbf{K_R}}{\mathbf{1+T_R}} \quad \textbf{(4)}$$

The Value of T_R ranged from 0.001 to 0.06 second.

COMPLETE MODEL OF AVR

Figure 2 shows the Automatic Voltage Regulator obtained by combining all the models from equation 1 to 4, with generator terminal voltage ($\mathbf{V_T}$) as output to the reference voltage ($\mathbf{V_{ref}}$) as input,

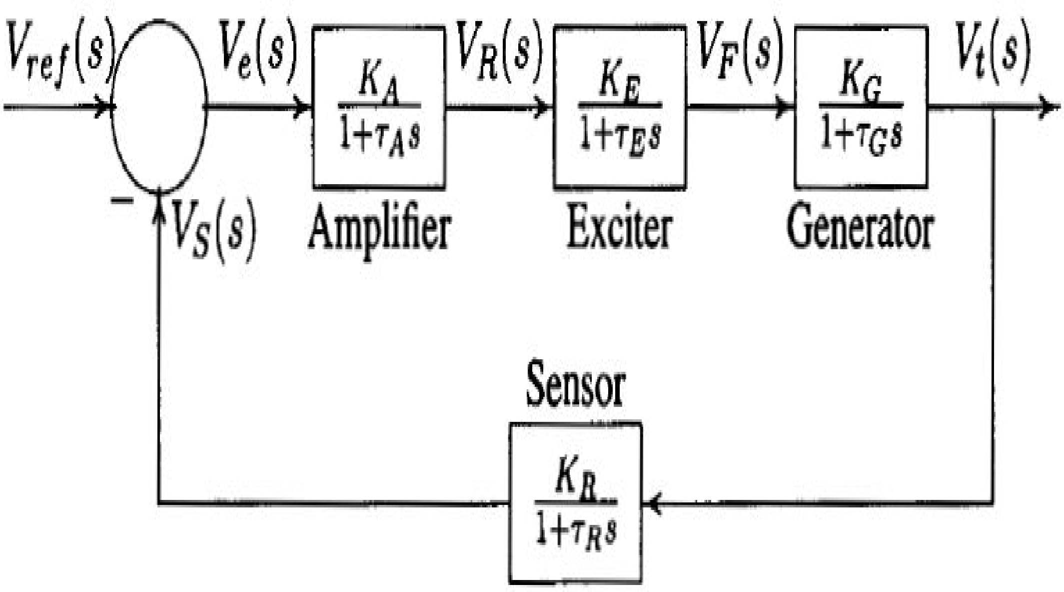

FIGURE 2: MATHEMATICAL BLOCK DIAGRAM OF AVR [18]

V. H∞ CONTROL DESIGN TECHNIQUE

The H∞ control method is utilized for stabilization and good robustness in term of performance. A controller is designed for a specific task and its theme is to control the magnitude of closed loop Transfer Function from input to output. The main advantage of H∞ control design method over the other classical control methods is its relevance to multivariable system's problem. All the H∞ control problems can be formulated in to a general control configuration. Let G (s) is the open loop transfer function of the plant and K(s) is the controller transfer function such that the closed loop system performs robustness and good performance. The controller K(s) will be derived keeping three criterions **[19].** They are,

1. Stability criterion: It states that the roots of the characteristic equation 1+G (s) K(s) = 0 should lie in the left half side of s plane.

2. Performance Criterion: It states that the sensitivity, $S(s) = \frac{1}{1+G\,(s)K(s)}$ to be small for all frequencies where disturbances and set point changes is large. Sensitivity is the transfer function between the output and disturbances of a system.

3. Robustness criterion: It demands for stability and performance to be maintained not only for the nominal model but also for a set of neighboring plant models that result from unavoidable presence of modelling errors. H∞ problem can be expressed in many areas of control. Due to such importance, it is very important to introduce a general model of such design so that everyone can use it according to their requirements. Figure 3 shows the general representation of control, **[19]**

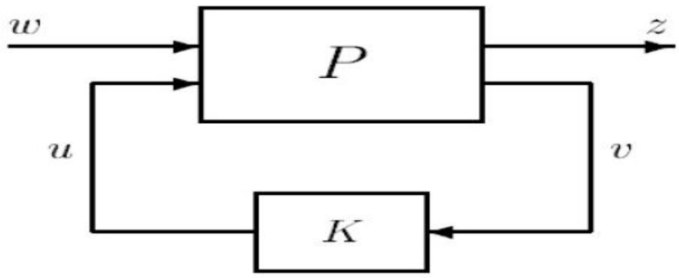

FIGURE 3: H∞ CONTROL GENERAL BLOCK DIAGRAM [19]

VI. H∞ ALGORITHM

H∞ controller synthesis splits a complex control problem into two separate sections, one dealing with stability, the other dealing with performance. The sensitivity function, S, and the complementary sensitivity function, T, are used in the controller synthesis. Sensitivity function is the ratio of output to the disturbance of a system and is given by equation, **[26]**

$$\mathbf{S} = \frac{\mathbf{1}}{(\mathbf{1+GK})} \qquad \textbf{(5)}$$

The other function is called 'Complementary Sensitivity Function (T)'. This is a transfer function from reference input 'r' to output 'y' and is given by equation,

$$\mathbf{T} = \frac{\mathbf{GK}}{(\mathbf{1+GK})} \qquad \textbf{(6)}$$

The ultimate aim of the robust control is to reduce the effect of disturbance on output. So sensitivity S and the complementary function T are to be reduced. For obtaining that it is enough to reduce the magnitude of |S| and |T|. This can be done by making $|S(j\omega)| < \frac{1}{W1(j\omega)}$ and $|T(j\omega)| < \frac{1}{W2(j\omega)}$. Where, W1 and W2 are the weight function assigned by the designer. W1 is the performance weighting function to limit the magnitude of the sensitivity function.

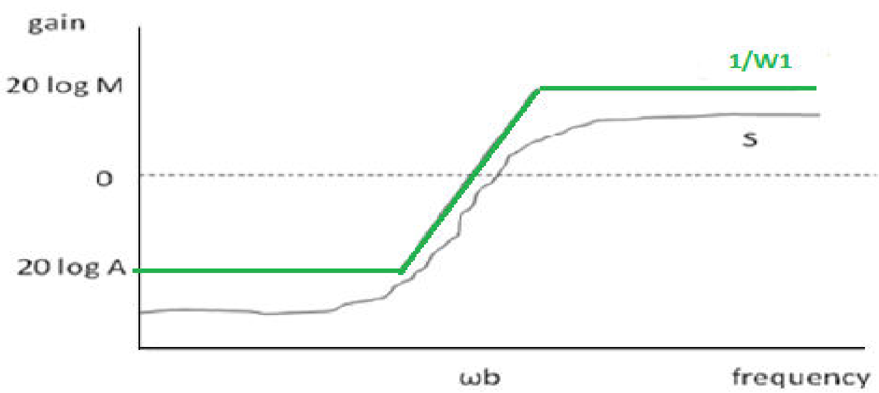

FIGURE 4. DESIRED NATURE OF FREQUENCY PLOTS OF PERFORMANCE WEIGHT FUNCTION AND SENSITIVITY FUNCTION [26]

W2 is the robustness weighting function to limit the magnitude of the complementary sensitivity function.

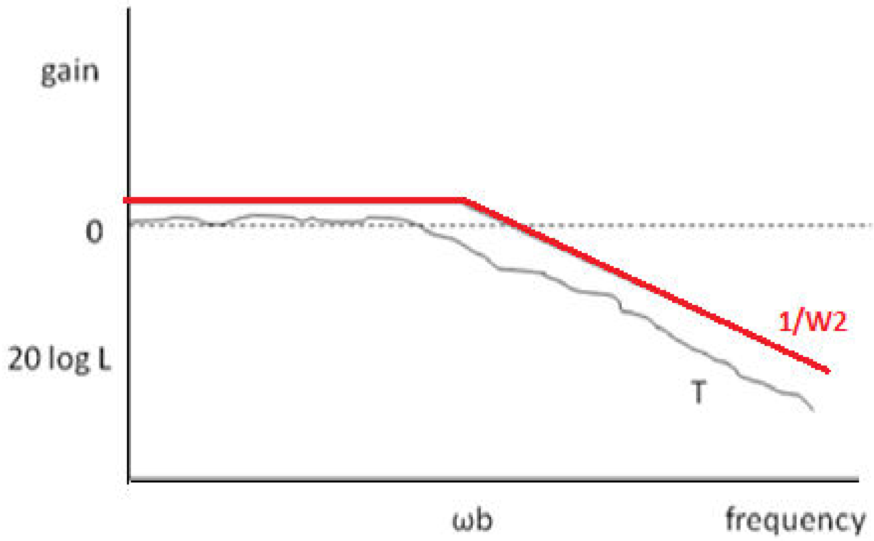

FIGURE 5: DESIRED NATURE OF FREQUENCY PLOTS OF ROBUSTNESS WEIGHT FUNCTION AND COMPLIMENTARY SENSITIVITY FUNCTION [26]

As mentioned earlier the robust controller is synthesized in order to make the H∞ norm of the plant to be as low as possible. In order to obtain this condition weight functions are added to the plant for loop shaping. The weight functions are in fact lead-lag compensators which can shape the frequency response of the system in the desired way. Loop shaping is done to make the frequency response of the plant with the weight functions to come in the desired manner. In loop shaping the parameters of the weight functions are changed to make the frequency response of the whole system to remain within limits **[15].** The control synthesis requires the plant transfer function, controller transfer function and the various weight functions to augment together. Thus an augmented plant model is made as shown in Fig 6.

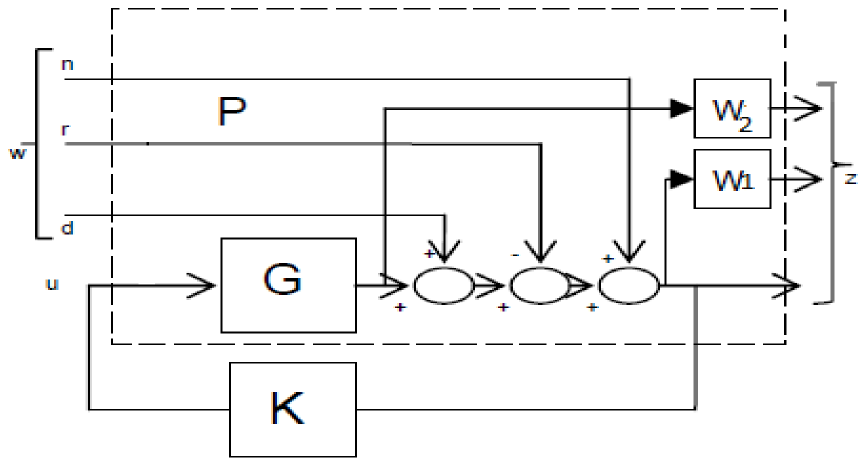

FIGURE 6: AUGMENTED PLANT MODEL FOR THE SYNTHESIS OF H∞ CONTROLLER

VI. AUTOMATIC WEIGHT SELECTION ALGORITHM

The choice of weights is very important in H∞ controller design as it counters the uncertainties and disturbances in the system.If in some cases there are no uncertainties in the model then these weights are used to increase the performance, robustness and stability of the system. Once, these weights are designed, they are used for the construction of H∞ controller. The controller designed will minimize the singular values of the closed loop transfer function of the Sensitivity function S and Complementary Sensitivity function T [25].As mentioned in the robust control theory the synthesis of the controller requires the selection of two weight functions. The work done by Jiankun Hu, Christian Bohn, H.R. Wu [17] suggests some methods for the selection of these weight functions for different plant transfer functions. **[17]** The works shown in reference also describes some ways for designing robust controller for uncertain plants. In all these design procedure the weighting functions are selected using trial and error method and later the H∞ controller is synthesized by loop shaping technique. An iteration work with assumed initial values is conducted to find out the weight functions. It is very difficult to achieve simultaneously meet all the requirements for the synthesis of robust controller. After many trial and error methods, a systematic procedure for the synthesis of H∞ controller is identified for AVR. This novel method makes adjustments in the parameters of the weight functions and enables the control synthesis algorithm to converge to a feasible solution for AVR in power systems meeting all the requirements of robust control. Even though there are no methods available for selecting the transfer functions for weight functions, certain generalization can be done by understanding the loop shaping procedure. Such an empirical formula to determine the performance and robustness weights for a general H∞ control problem is suggested by skojested **[26]** and is given in equations 7 and 8,

$$w1 = \frac{s/M + w_b}{s + w_b A} \qquad \textbf{(7)}$$

$$w2 = \frac{Ls+1}{2(0.5Ls+1)} \qquad \textbf{(8)}$$

Where W_1 is the performance weighting function, W_2 is the robustness weighting function, ‘ w_b ’ is the cut off frequency, ‘M’ is the gain for high frequency disturbances and ‘A’ is the gain for low frequency control signal and L is a constant. The plots, Fig 4 & Fig 5 show the nature of $\frac{1}{W1(j\omega)}$,S and $\frac{1}{W2(j\omega)}$, T to be satisfied for the synthesis of H∞ controller. This can be made by closely shaping the $\frac{1}{W1(j\omega)}$ and $\frac{1}{W2(j\omega)}$ plots. This loop shaping technique consists of adjusting the various parameters of the weight functions. A generalization is made on how these parameters are to be varied to closely shape the curves to make a robust H∞ controller synthesis algorithm. The flow chart of the automatic weight selection algorithm is shown in Fig 7. The objective of the algorithm is to modify the weights until the various performance criterions specified in robust control theory is met. As per the robust control criterion, the algorithm searches for a minimum value of cost function γ along with shaping the closed loop responses of sensitivity function, and complementary sensitivity function.

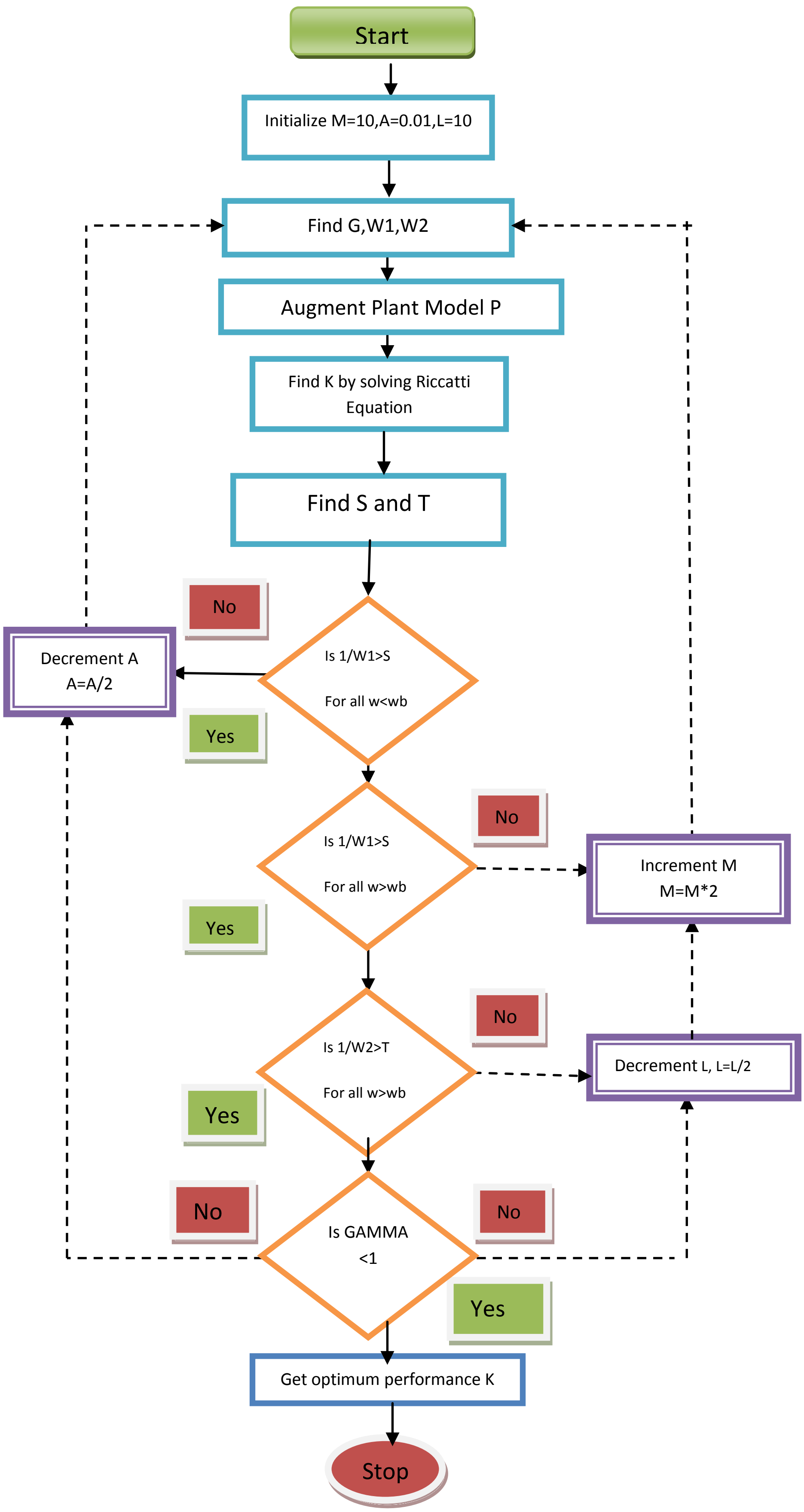

FIGURE 7: AUTOMATIC WEIGHT SELECTION ALGORITHM

VII. SIMULATION AND RESULTS

RESPONSE OF AVR WITHOUT ANY CONTROLLER

The MATLAB-Simulink model of the AVR system without any controller is shown in figure 8. A step reference voltage signal of amplitude 1 pu is applied to the system.

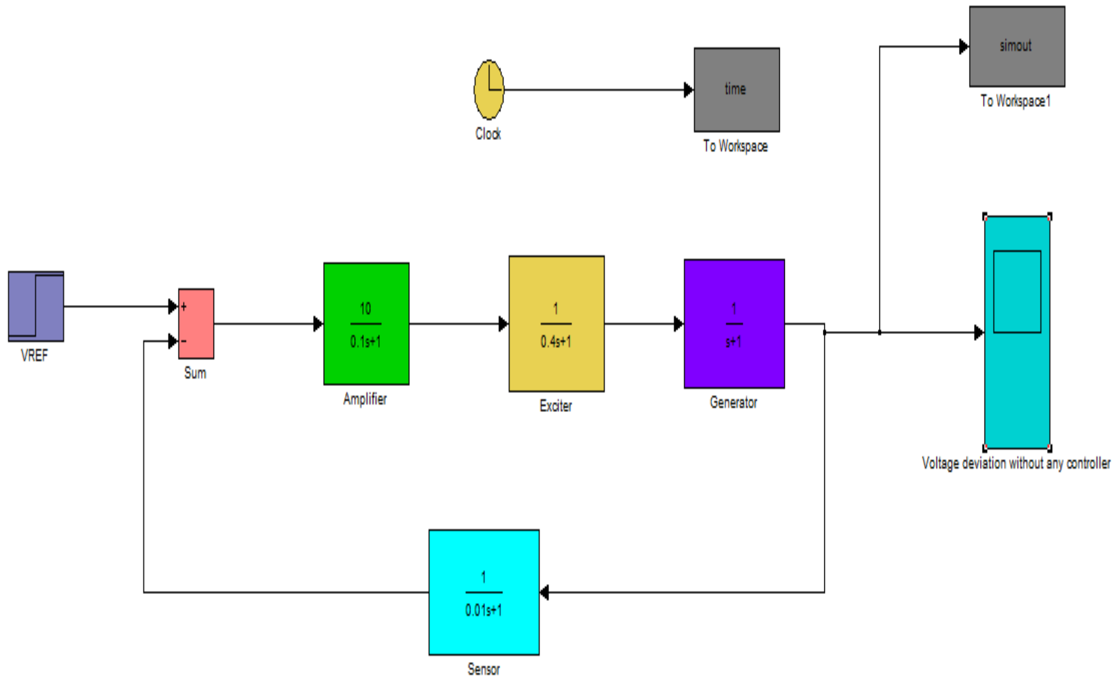

FIGURE 8: SIMULINK MODEL OF AVR WITHOUT ANY CONTROLLER

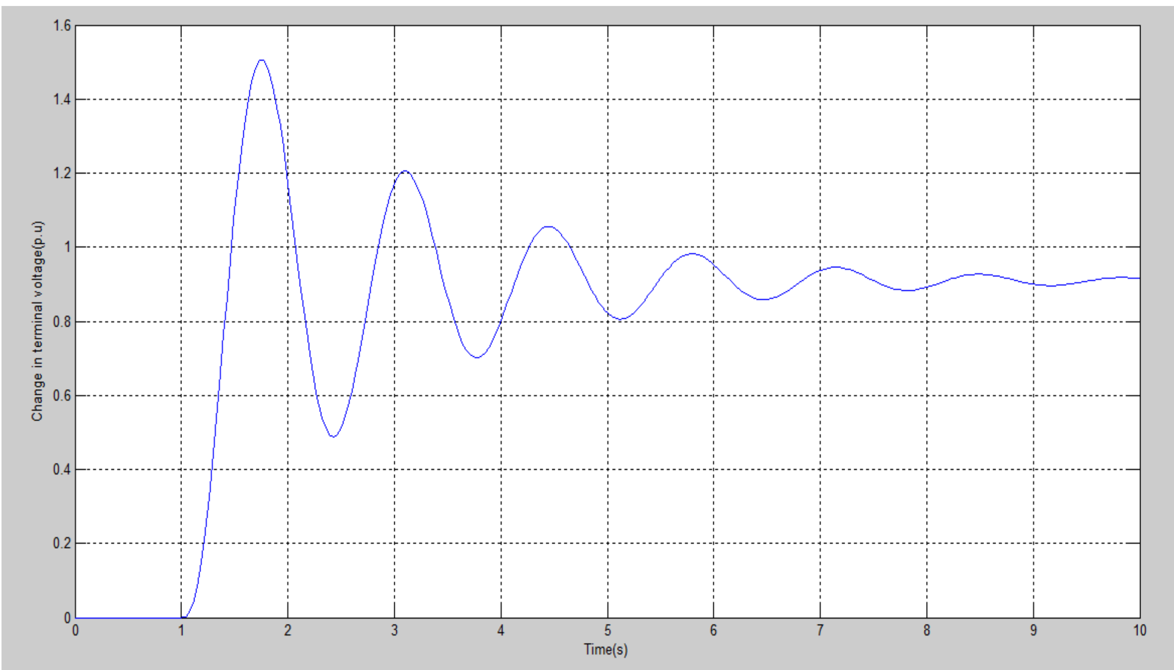

FIGURE 9: STEP RESPONSE OF CHANGE IN THE TERMINAL VOLTAGE WITHOUT ANY CONTROLLER

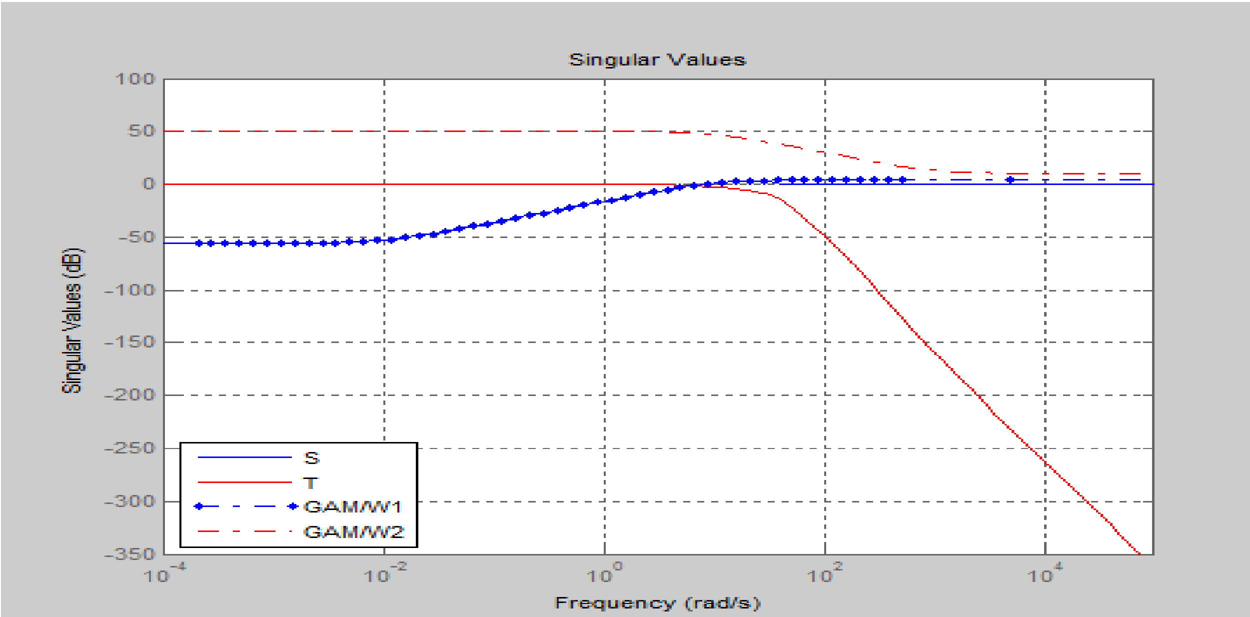

FIGURE 10: SINGULAR VALUES OF AVR

INPUT WEIGHTING FUNCTION

W1 is the input weighting function. It is used to limit the magnitude of the sensitivity function as shown in figure 11. W1 is obtained by using automatic weight selection algorithm,

$$W1 = \frac{0.1(s + 10)}{(s + 0.01)}$$

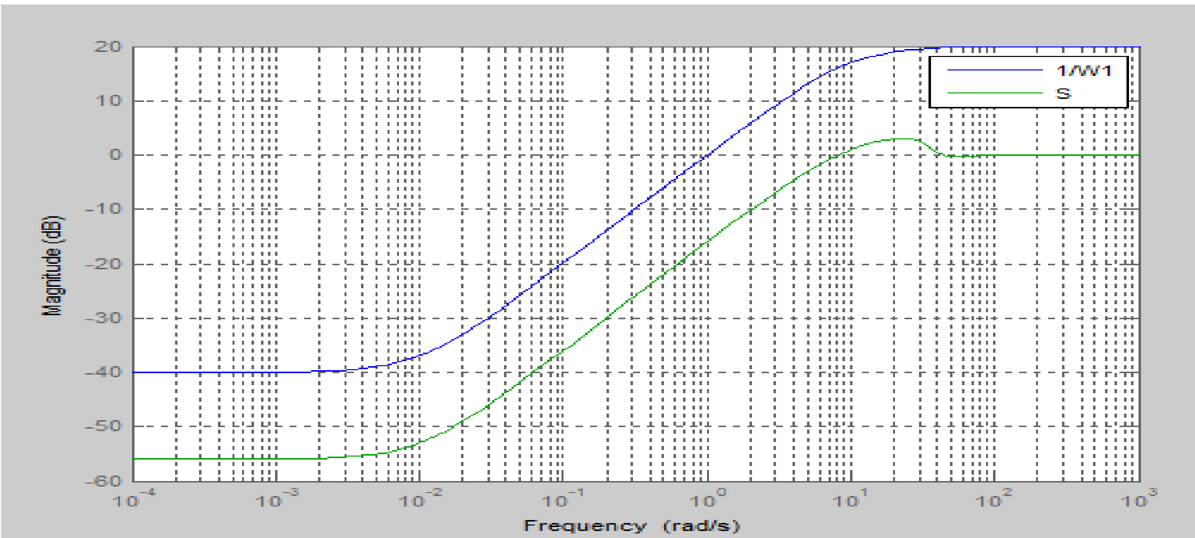

FIGURE 11: INPUT WEIGHTING FUNCTION '1/W1' LIMITING THE MAGNITUDE OF SENSITIVITY FUNCTION 'S'

OUTPUT WEIGHTING FUNCTION

W2 is the robustness weighting function. It is used to limit the magnitude of the complementary sensitivity function 'T' as shown in figure 12. W2 is obtained by using automatic weight selection algorithm,

$$W2 = \frac{0.005(s + 10)}{(s + 1000)}$$

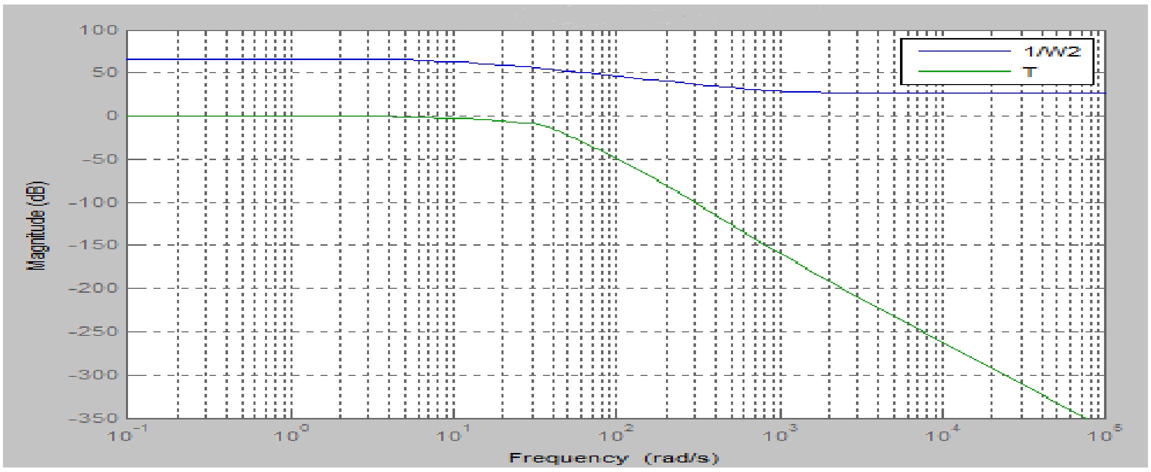

FIGURE 12: OUTPUT WEIGHTING FUNCTION '1/W2' LIMITING THE MAGNITUDE OF COMPLEMENTARY SENSITIVITY FUNCTION 'T'

RESPONSE OF AVR USING H∞ CONTROLLER

As we know that our system was unstable before H∞ Controller. Now we have designed H∞ Controller and performed a closed loop analysis. We can see from the figure 13, that the system has become stable and tracks the reference input. Settling time of the closed loop system is 0.448 seconds second and rise time is 0.22 seconds.

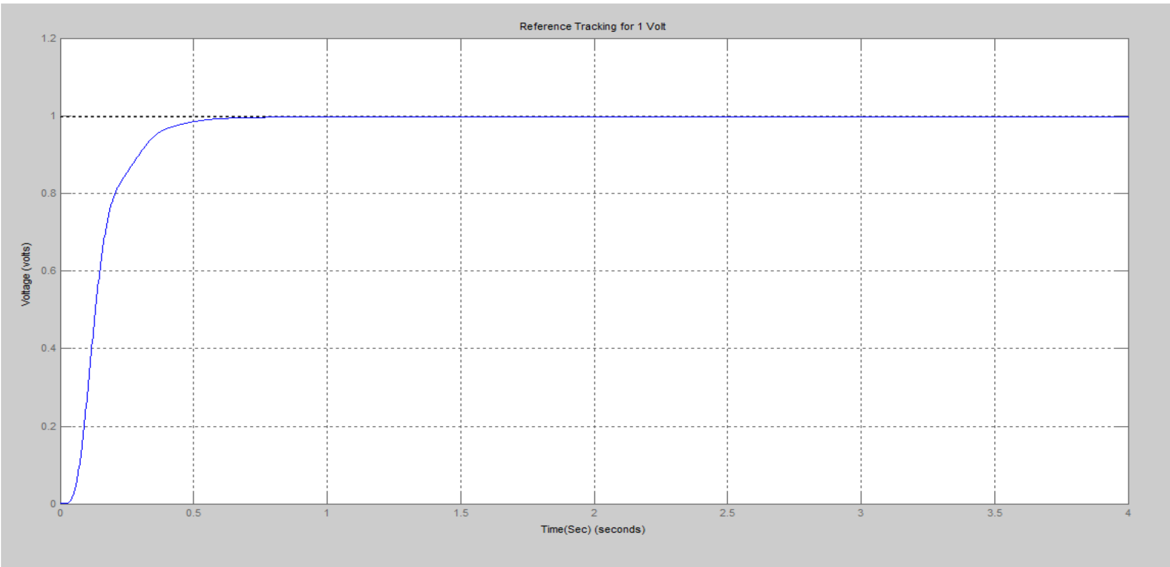

FIGURE 13: STEP RESPONSE OF CHANGE IN THE TERMINAL VOLTAGE WITH H∞ CONTROLLER

S#	PARAMETERS	AVR WITHOUT CONTROLLER	AVR WITH H∞ CONTROLLER
1	% Overshoot	50.75	0
2	Rise time	0.468	0.2
3	Settling time	7.1	0.448

Table 1: COMPARISON OF AVR WITH AND WITHOUT H∞ CONTROLLER.

REFERENCE TRACKING

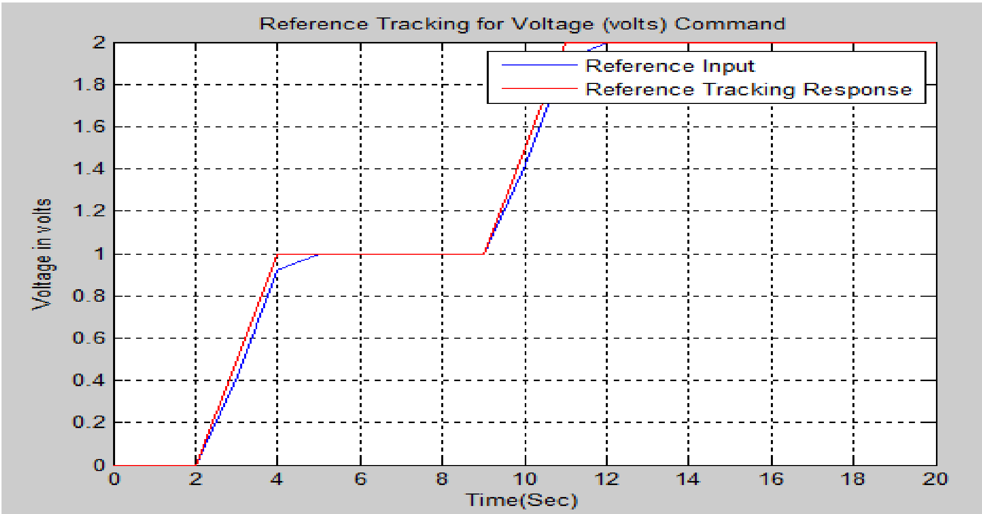

FIGURE 14: REFERENCE TRACKING RESPONSE OF AVR

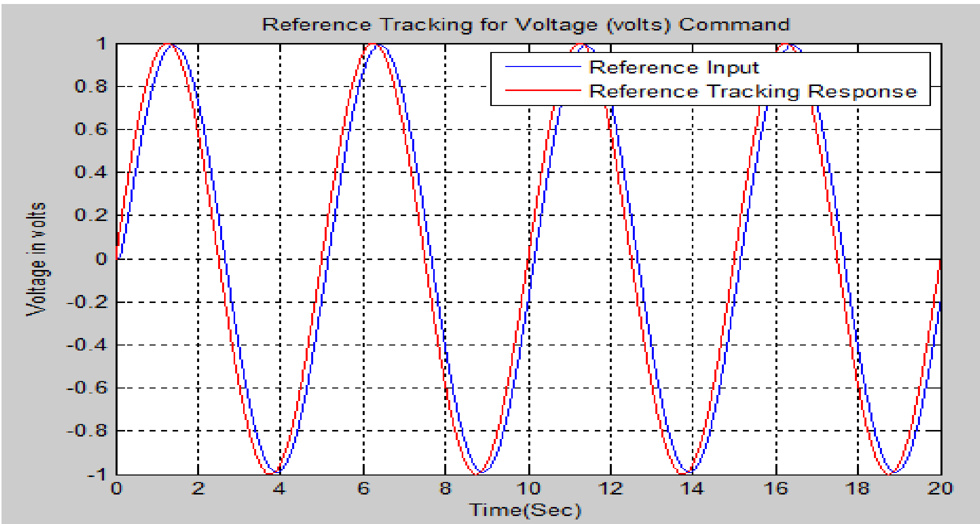

FIGURE 15: SINUSOIDAL RESPONSE OF AVR

CONCLUSION

It has been shown that H∞ control technique can effectively be applied with AVR. The results show that the performance of AVR using H∞ control is high compared to conventional AVR. The tuning of weighting functions using 'Automatic Weight Selection Algorithm' enables the control synthesis algorithm to converge to a feasible solution meeting all the requirements of robust control. Simulations results show the efficient working of the controller. Simulation contains the closed loop step response of the system. It was found that the system becomes stable and tracks the reference input. Reduction in Settling time and rise time is observed. The controller is also tested for voltage deviation, the AVR will attain the required voltage corresponding to the given reference voltage command. The simulation results show that the proposed controller is robust against disturbances. At the completion of this research, there are many key points which are learnt about the H∞ design procedure. H∞ controller has the capability to maintain stability and robustness of AVR under the presence of load disturbances in power system. The control effort generated by this technique is under limits and can be easily applied to the plant.

APPENDIX

Name of Parameter	Gain	Time Constant
Amplifier	K_A=10	T_A=0.1
Exciter	K_E=1	T_E=0.4
Generator	K_G=1	T_G=1
Sensor	K_R=1	T_E=0.01

TABLE 2: PARAMETERS OF AVR

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